

**A Dedicated Hadronic
B-Factory: Accelerator Considerations**

**Gerald P. Jackson
FNAL**

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Outline of the Talk

This talk is broken up into two halves:

- 1) Overview of General Considerations for an Optimized, Dedicated, Green-Field Hadron Collider beyond the LHC for B-Physics.
- 2) Suggestion (Recruitment) to Join onto a Low-Cost Hadron Collider Project which "Some People" Want to Propose "Very Soon".

Apologies/Fine Print:

Though I have designed, commissioned, and operated many storage rings, this is the first time I have attempted to look at the needs of a dedicated hadronic B-Factory. Therefore, please excuse me if I make some blatant mistakes or fail to reference a piece of work you are familiar with.

All suggestions, comments, criticisms, and praise are encouraged and welcome.

Detector Needs

A B-Physics optimized detector in a dedicated hadron collider has specific preferred beam conditions. I am assuming that they are:

- 1) Less than or equal to 1 interaction/crossing. For future calculations let us use the symbol β to refer to this parameter.
- 2) Bunch crossing frequency no higher than 30 MHz (a bunch spacing no closer than 33 nsec). We will use the symbol T_b to refer to the bunch spacing.
- 3) Reasonably small radial beam size for vertex triggering. This rms radius of the beam, which has a Gaussian+halo spatial distribution, is called $\sigma_{x,y}$ and is assumed to be smaller than 100 μm .
- 4) The rms bunch length should be infinitesimally short if one operates at $\beta = 1$ but can be much longer ($\sigma_s \sim 30 \text{ cm}$) if money is sunk into more silicon and more interaction per crossing are inevitable or desired.

Interaction Region Length

From an accelerator physics point of view, the magnetic lattice of a collider generates a focussing envelope called the beta-function.

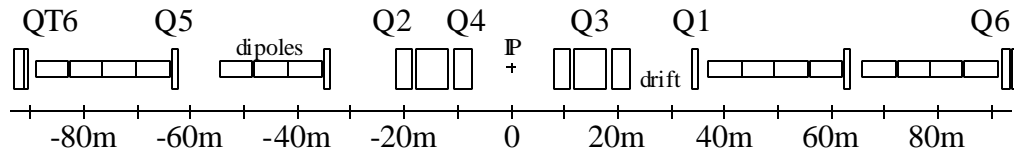
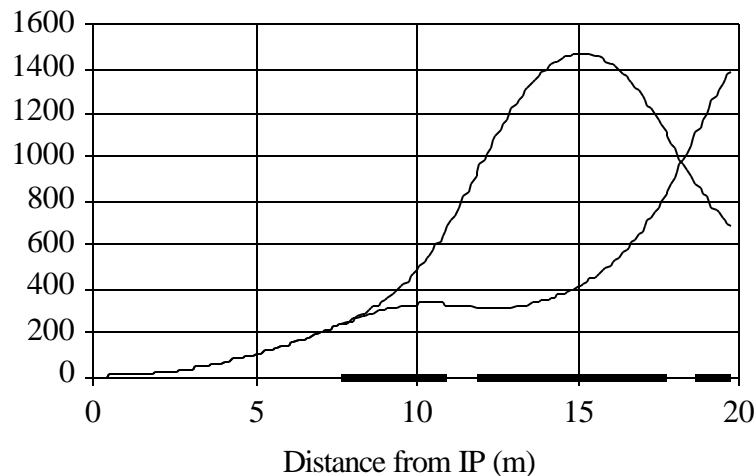


Figure 1.1: Sketch of the magnet placements and labels around each interaction point.



Horizontal and vertical beta functions in one half of a high-PT Tevatron Collider interaction region. The positions of the Q4, Q3, and Q2 quadrupoles are shown along the horizontal axis.

In a straight section devoid of focussing magnets the where the transverse shape of the beam is round (which is traditional for hadron colliders, unlike the flat beams in electron colliders), the rms size of the beam ? depends on longitudinal position s according to the equation

$$\sigma_{x,y}^2(s) = \sigma_{x,y}^2 \left[1 + \left(\frac{s}{\beta^*} \right)^2 \right]$$

where β^* is the accelerator lattice parameter called beta-star and σ_0 is the transverse rms size of the beam at the interaction point.

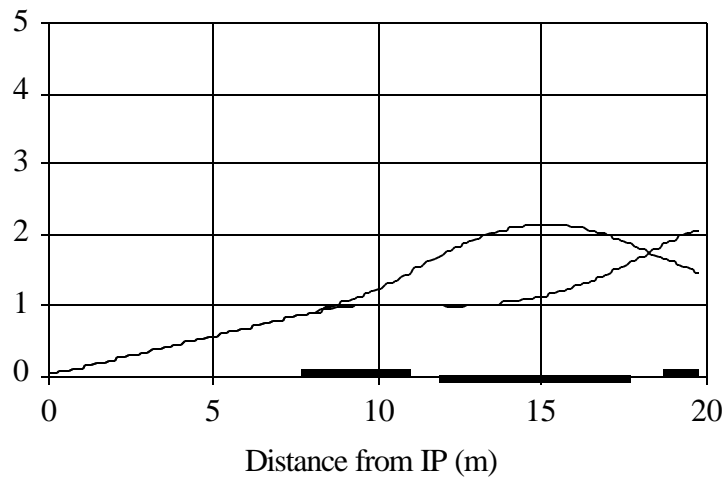


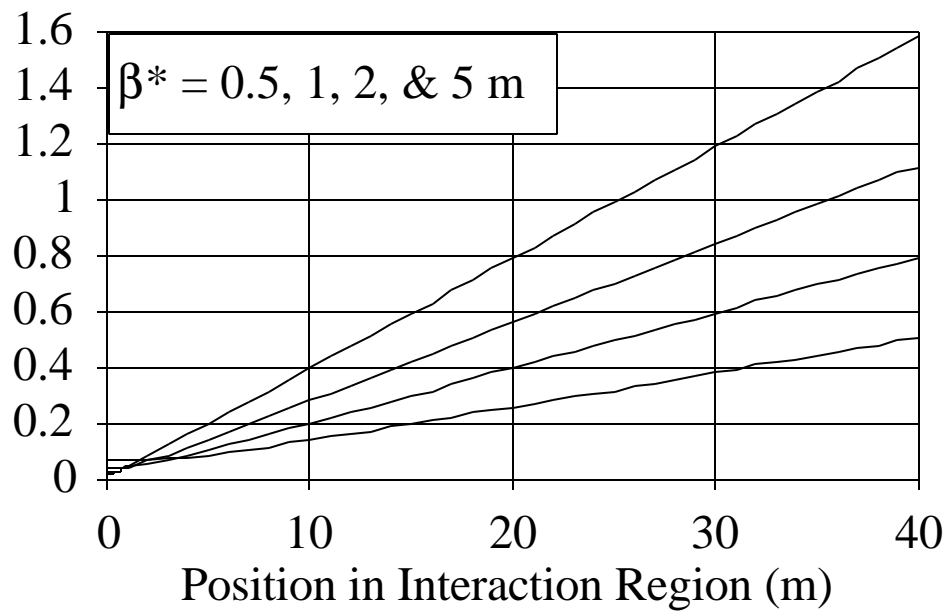
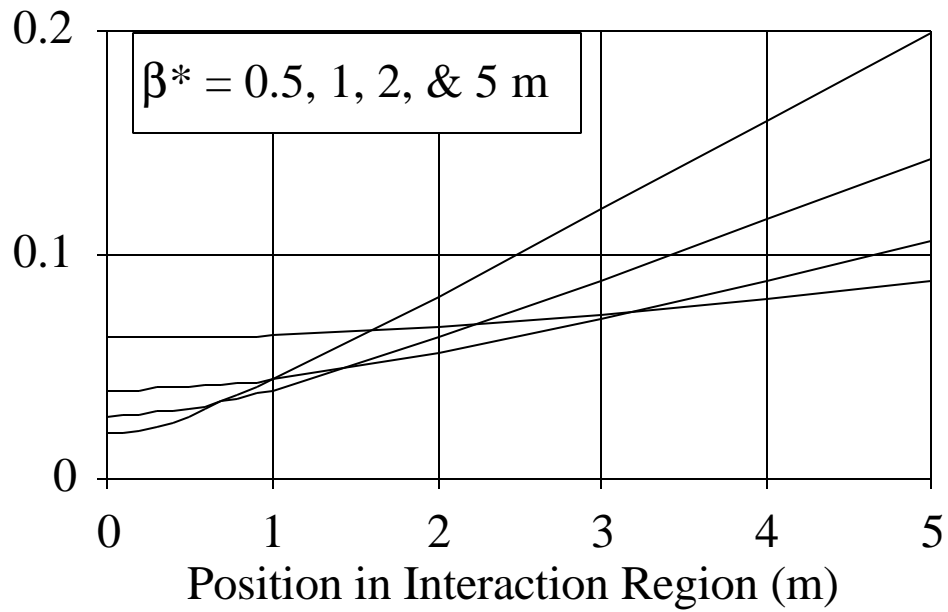
Figure 2.1: Horizontal and vertical beam sizes in one half of a Tevatron Collider interaction region.

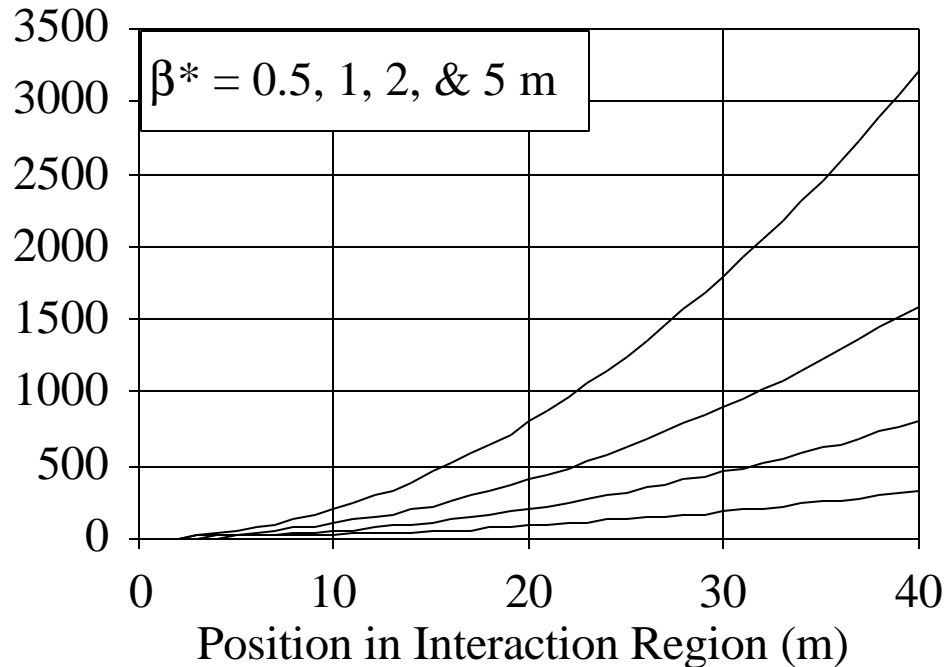
Note that for $s \gg \beta^*$ the beam size grows linearly with distance. The relationship between the rms beam size at the collision point and β^* is

$$\sigma_{x,y} = \sqrt{\frac{\epsilon_n \beta^*}{6\beta_r \gamma_r}}$$

where ϵ_n is the 95% normalized transverse emittance (temperature) and β_r and γ_r are the relativistic velocity and energy of the protons (antiprotons).

The following plots were for a 15p mmmr 95% invariant emittance beam at and energy of 3 TeV.





Can low-beta quadrupoles be built to handle these ? *s and interaction region lengths?

The job of the first of three ~equal strength low-beta quadrupoles is to focus trajectories in one transverse plane into a parallel beam. For magnets which are short compared to the length of the interaction region, this means that the focal length is equal to the interaction region length.

If the length of the interaction region scales with energy, the same quadrupoles can always be used. This is because for a fixed magnetic field gradient the focal length also proportional to energy.

As the region gets longer, the beam size increases proportionally. But as energy increases, the beam size is reduced by the square root of the energy. Therefore the beam size at the entrance to the first quadrupole only increases as the square root of the energy.

Luminosity Calculation

The economics of proton and antiproton beam production are completely different given the fact that one gets 15 antiprotons for every 1 million protons striking the production target. Therefore, the calculation of luminosity for proton-antiproton and proton-proton operations are presented separately below.

Proton-Antiproton Collisions

The luminosity at each HEP detector is

$$L = \frac{N_P (N_A B) f_o (6\beta_r \gamma_r)}{2\pi \beta^* (\epsilon_{n_P} + \epsilon_{n_A})} H\left(\frac{\beta^*}{\sigma_s}\right) \frac{1}{\sqrt{1 + \frac{2\alpha^2 \sigma_s^2 (\beta_r \gamma_r)}{\beta^* (\epsilon_{n_P} + \epsilon_{n_A})}}}$$

where θ is the crossing half-angle, N_P and N_A are the bunch intensities, f_o is the revolution frequency, σ_s is the rms bunch length, and H is the hour-glass factor which has the form

$$H(x) = \sqrt{\pi} x [1 - \Phi(x)] e^{x^2}$$

The ultimate limit to luminosity in hadron colliders to date has been the beam-beam interaction. This limit has been a total beam-beam linear beam-beam tune shift ξ of approximately 0.025 where ($r_p = 1.535 \times 10^{-18}$ m)

$$\xi = \frac{3r_p}{2\pi} \frac{N}{\epsilon_n} N_{IP}$$

The ratio of the proton bunch intensity to emittance is limited by the total beam-beam tune shift suffered at all interaction regions.

Plugging the equation for this tune shift into the equation for luminosity per interaction region yields the result

$$L = \frac{(N_A B)}{N_{IP} \beta^*} \frac{\xi_{\max} f_o (6\beta_r \gamma_r)}{3r_p \left(1 + \frac{\epsilon_{nA}}{\epsilon_{nP}} \right)} \dots$$

where the factors whose values can be modified appear in the left fraction on the RHS of the equation. The quantity $(N_A B)$ is just the total antiproton intensity injected into the Tevatron, independent of the bunch spacing.

Unique to a dedicated B-physics collider there is an added constraint that the number of interaction per crossing is limited to $\Omega \sim 1$. This quantity is equal to

$$\Omega = \frac{\sigma_{\text{inel}} L}{f_o B}$$

where σ_{inel} is the inelastic cross-section. Note that $f_o B$ is limited by the detector trigger rate (30 MHz). Therefore, the detector limitations completely determine the maximum luminosity ($5.4 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$).

By plugging this equation into the above luminosity equation, and noting that the values of the hour-glass and crossing-angle form factors are unity, one gets the constraint that for some Ω_{\max} ,

$$B_{\min} = \frac{(N_A B)}{\Omega_{\max} N_{IP} \beta^*} \frac{\xi_{\max} \sigma_{\text{inel}} (6\beta_r \gamma_r)}{3r_p \left(1 + \frac{\epsilon_{nA}}{\epsilon_{nP}} \right)}$$

As the energy of the ring increases, the number of bunches must increase proportionally.

If one assumes that every antiproton which is available is used, the following table can be generated from the above equation. Most parameters are kept artificially constant to show how the bunch spacing is effected by energy.

Parameter	Tev	Tev-B	"LHC"	VLHC
Beam Energy (TeV)	1	3	7	50
Beam-Beam Tune Shift	0.025	0.025	0.025	0.025
Interaction Regions	2	2	2	2
Interactions/Crossing	1	1	1	1
Inelastic Cross-Section (mb)	49	49	49	49
Total Antiprotons (E12)	10	10	10	10
Beta-Star (m)	5	5	5	5
Minimum # of Bunches	92	276	643	4595
Revolution Frequency (kHz)	48	8.8	8.8	0.5
Bunch Frequency (MHz)	4.4	2.4	5.7	2.3
Luminosity ($10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$)	79	44	102	44

- The Tevatron and LHC circumference assume the existing tunnels, while for Tevatron-B and VLHC high packing fraction 2 Tesla superferic magnets are assumed.
- The choice of 5 m for beta-star assumes that a ± 40 m long interaction region is always desired, and that the beta-function at the low-beta quadrupoles is ≈ 350 m.

Proton-Proton Collisions

The luminosity at each HEP detector is

$$L = \frac{N^2 B f_o (6\beta_r \gamma_r)}{4\pi \beta^* \epsilon_n} H\left(\frac{\beta^*}{\sigma_s}\right) \frac{1}{\sqrt{1 + \frac{\alpha^2 \sigma_s^2 (\beta_r \gamma_r)}{\beta^* \epsilon_n}}}$$

Again, the limit to luminosity to the proton brightness is the beam-beam interaction.

$$\xi = \frac{3r_p}{2\pi} \frac{N}{\epsilon_n} N_{IP}$$

Plugging this constraint into the luminosity equation yields the result

$$L = \frac{N B f_o (6\beta_r \gamma_r)}{6\beta^*} \frac{\xi_{\max}}{r_p N_{IP}}$$

Note that the luminosity is proportional to proton current in the accelerator and the beam energy.

Again, there is an added constraint that the number of interaction per crossing is limited to ~ 1 . This quantity is equal to

$$\Omega = \frac{\sigma_{\text{inel}} L}{f_o B}$$

Note that $f_o B$ is limited by the detector trigger rate (30 MHz). Therefore, the detector limitations completely determine the maximum luminosity ($5.4 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$).

Plugging this constraint into the above luminosity equation, one finds that the constrained quantity is the proton bunch intensity. The number of bunches is unconstrained, so the luminosity is unconstrained until the crossing rate exceeds the trigger speed.

$$N_{\max} = \frac{\Omega_{\max} \beta^* 6 r_p N_{\text{IP}}}{\sigma_{\text{inel}} (6 \beta_r \gamma_r) \xi_{\max}}$$

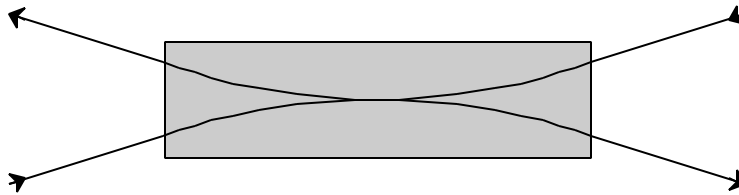
The following table can be generated from the above equation. Most parameters are kept artificially constant to show how the bunch spacing is effected by energy.

Parameter	Tev	Tev-B	"LHC"	VLHC
Beam Energy (TeV)	1	3	7	50
Beam-Beam Tune Shift	0.025	0.025	0.025	0.025
Interaction Regions	2	2	2	2
Interactions/Crossing	1	1	1	1
Inelastic Cross-Section (mb)	49	49	49	49
Beta-Star (m)	5	5	5	5
Max. Bunch Intensity (E9)	175	39	16	2.4
Max. Bunch Freq. (MHz)	27	27	27	27
Total Bunches/Beam	558	3023	3023	50,379
Luminosity ($10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$)	540	540	540	540

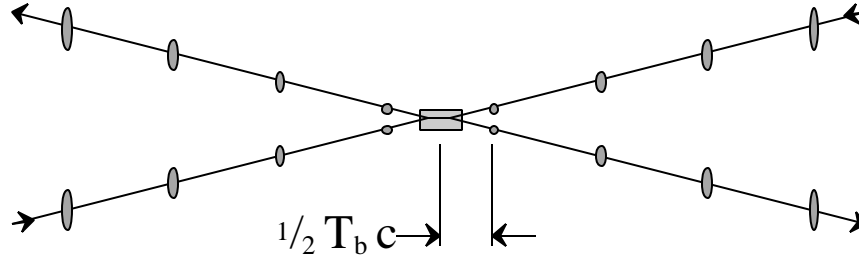
- The choice of 5 m for beta-star assumes that a ± 40 m long interaction region is always desired, and that the beta-function at the low-beta quadrupoles is ≈ 350 m.

Proton-Proton IR Geometry

- The goal is to always have head-on beam-beam collisions without crossing angles and electrostatic separators.
- With a dipole magnet at the center of the interaction region, this is an easy criterion to achieve.



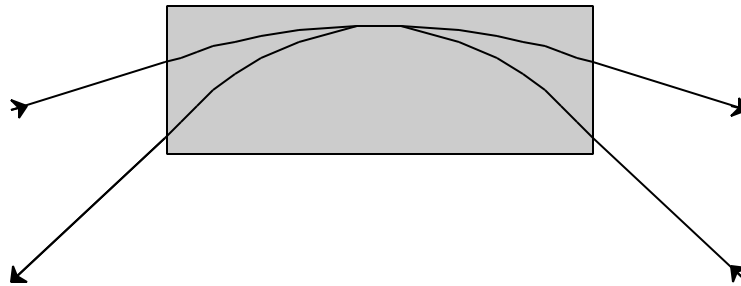
- At the parasitic crossing points the beam centers should be separated by more than 6 rms beam sizes. But to separate the beams into their respective accelerators again, at least ± 10 rms beam sizes is needed.



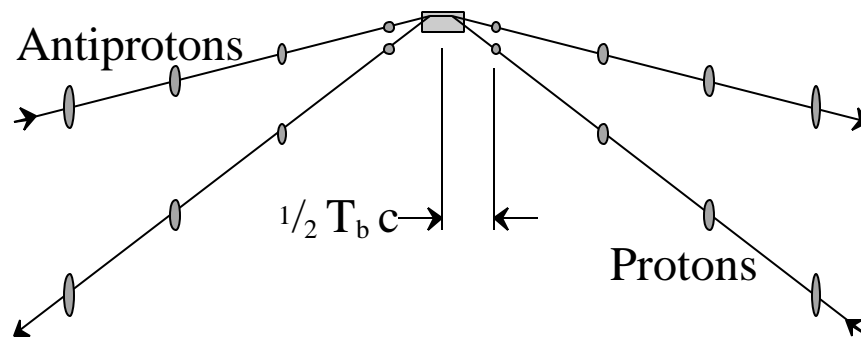
Parameter	Tev	Tev-B	"LHC"	VLHC
Beam Energy (TeV)	1	3	7	50
Emittance (pmmmr 95% inv)	15	15	15	15
Beta-Star (m)	5	5	5	5
Beam Divergence (μ rad)	22	13	8.2	3.1
Min. Beam Deflection (μ rad)	220	130	82	31
Min. Dipole Field (T-m)	1.5	2.6	3.8	10.3
Beam Sep. @ 40m (mm)	18	10.4	6.6	2.5
Bunch Spacing (nsec)	38	38	38	38
Nearest Secondary Xing (m)	5.6	5.6	5.6	5.6

Proton-Antiproton IR Geometry

- The goal is to always have head-on beam-beam collisions without crossing angles and electrostatic separators.
- With a dipole magnet at the center of the interaction region, this is an easy criterion to achieve if one institutes asymmetric energy collisions.



- At the parasitic crossing points the beam centers should be separated by more than 6 rms beam sizes. But to separate the beams into their respective accelerators again, at least ± 10 rms beam sizes is needed.



Parameter	Tev	Tev-B	"LHC"	VLHC
Beam Energy (TeV)	1x.33	3x1	7x2.3	50x17
Beam Divergence (μ rad)	22x38	13x23	8.2x14	3.1x5.4
Min. Pbar Deflectn (μ rad)	220	130	82	31
Min. Dipole Field (T-m)	1.5	2.6	3.8	10.3
Beam Sep. @ 40m (mm)	18	10.4	6.6	2.5

Bunch Length

What should be expected for the bunch length, and hence the luminous length?

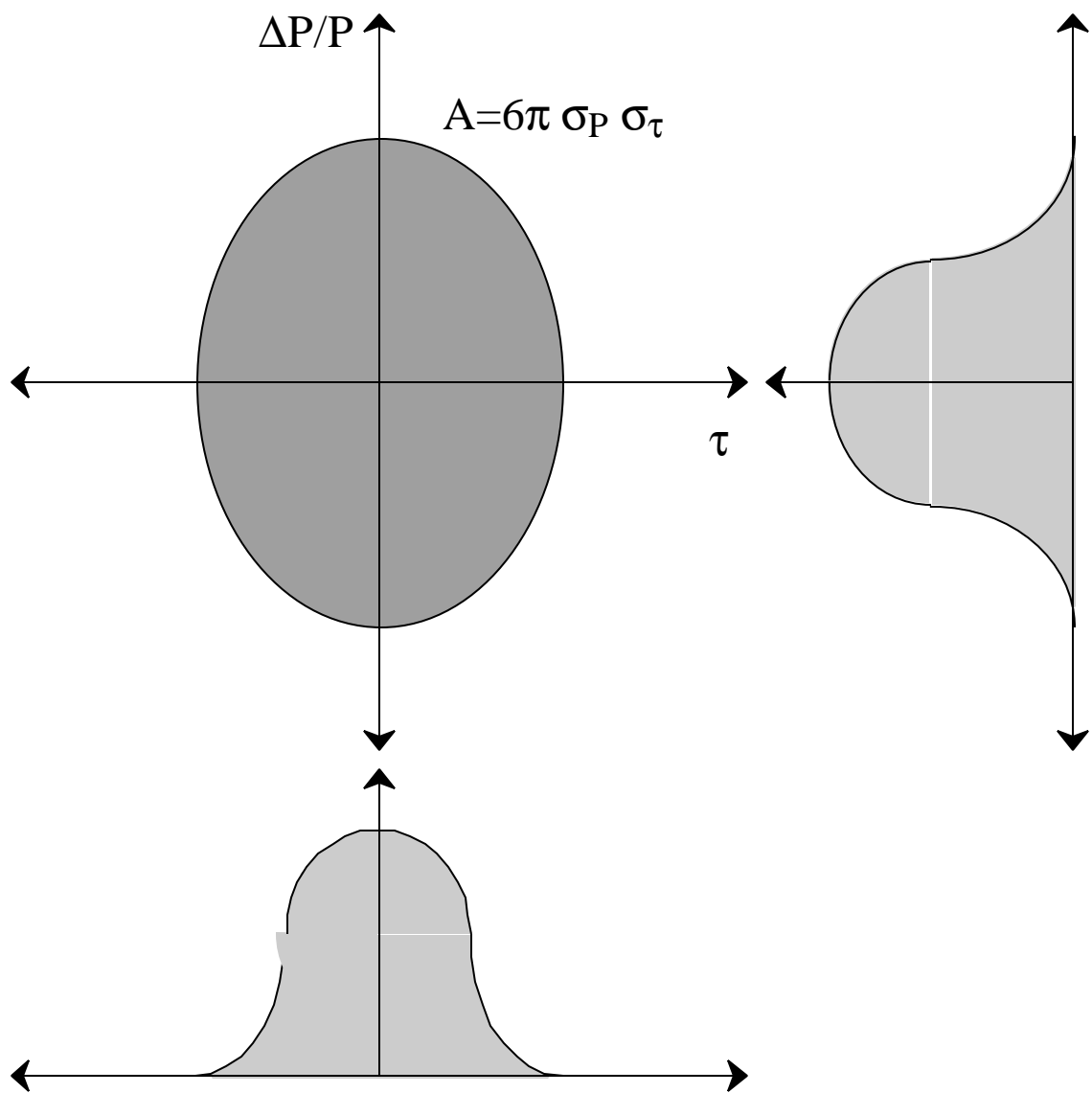
The answer to this question depends on the intensity per bunch needed to reach the desired luminosity. To zeroth order, proton bunch intensities below 1×10^{11} do not require any special RF manipulations. With a high energy recycling storage ring for antiprotons, RF manipulations are never necessary for large numbers of antiprotons bunches.

Just as there is a normalized emittance in the transverse plane which defines an energy independent beam temperature, in the energy plane there is also an invariant bunch area. The conjugate coordinates defining this area are momentum spread and time spread.

The RF system is used to mold the shape of this "phase space" in order to generate a desired bunch length. But in order to halve the bunch length, 16 times the RF gradient must be generated. This can be accomplished by turning up the RF voltage by 16x (256x times more power to halve the bunch length), increase the RF frequency by 16x (better have bunches which are already shorter than the new RF wavelength), or some combination of the two.

Invariant bunch areas of 0.1-0.5 eV-sec are achievable for hadronic B-Factories when special RF manipulations are not called for. For a fixed RF gradient, the bunch length scales with the square root of the bunch area. In the Tevatron, which has 1 MV of RF at 53 MHz, the longitudinal bunch area during Run I was 3 eV-sec, with a resultant rms bunch length of 45 cm.

Without special RF manipulations, the Tevatron bunch area could be reduced by 10x, which means that the bunch length would shrink by 3x. As this beam is accelerated, for the same RF gradient, the bunch length shrinks further as the square root of the energy increase.



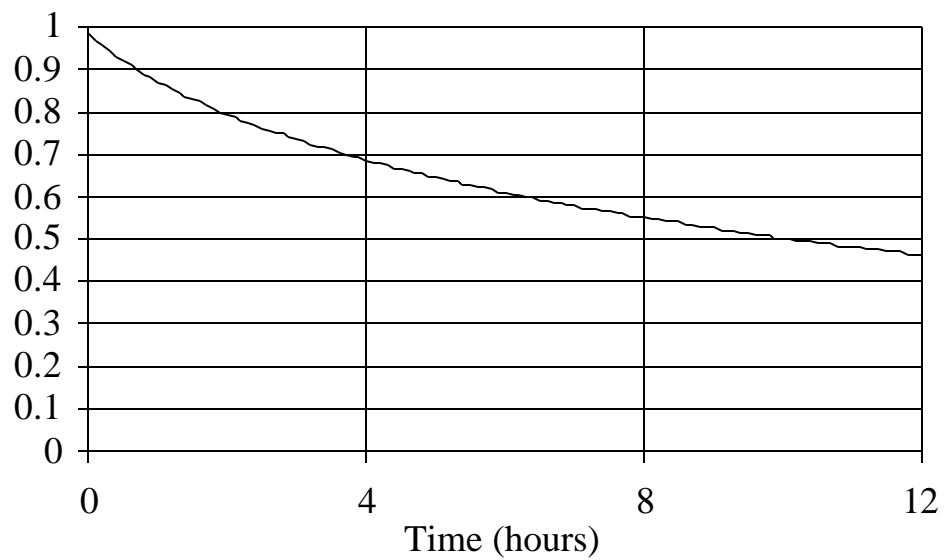
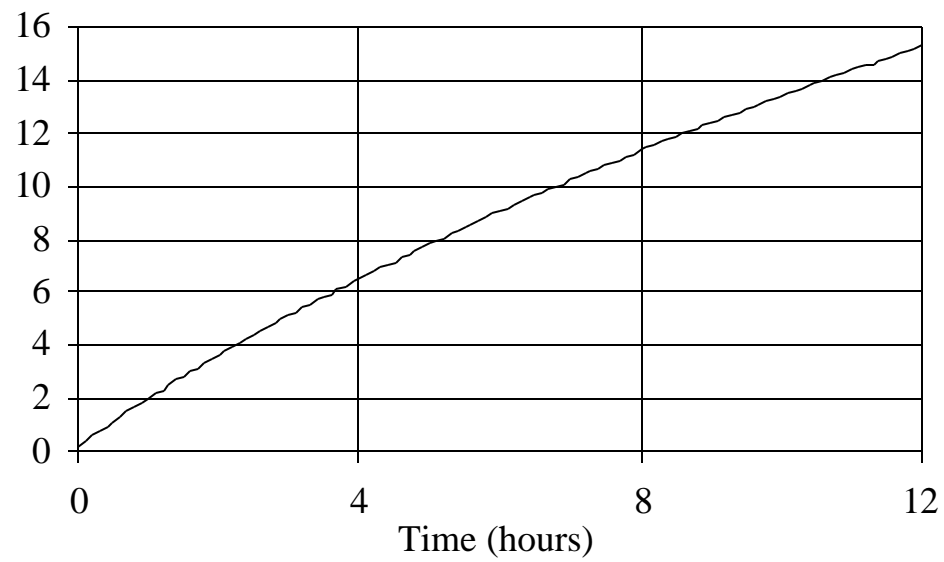
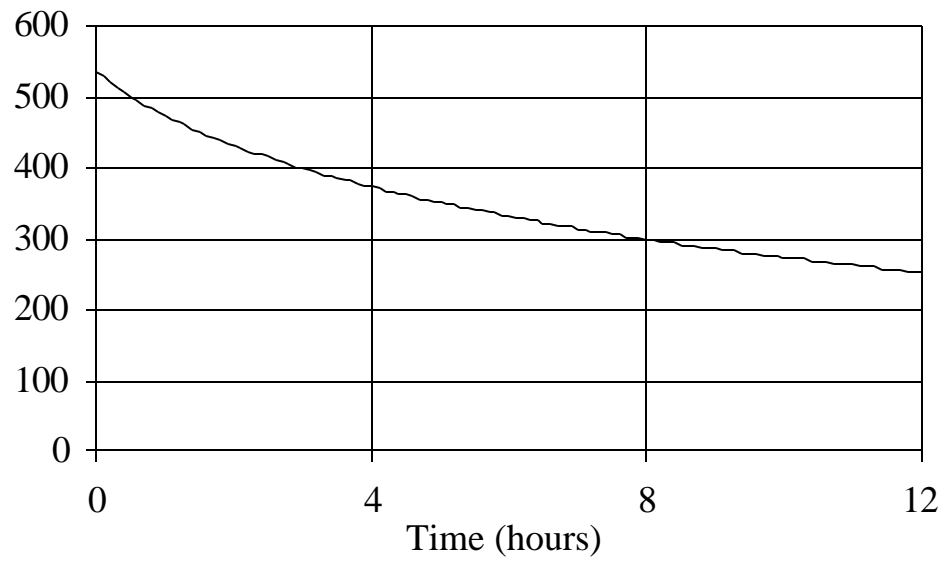
Luminosity Evolution Simulations

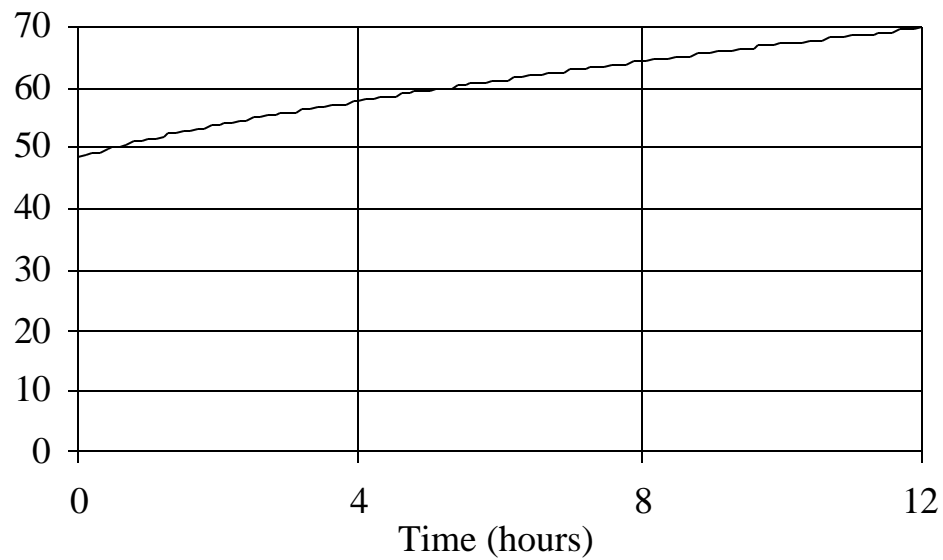
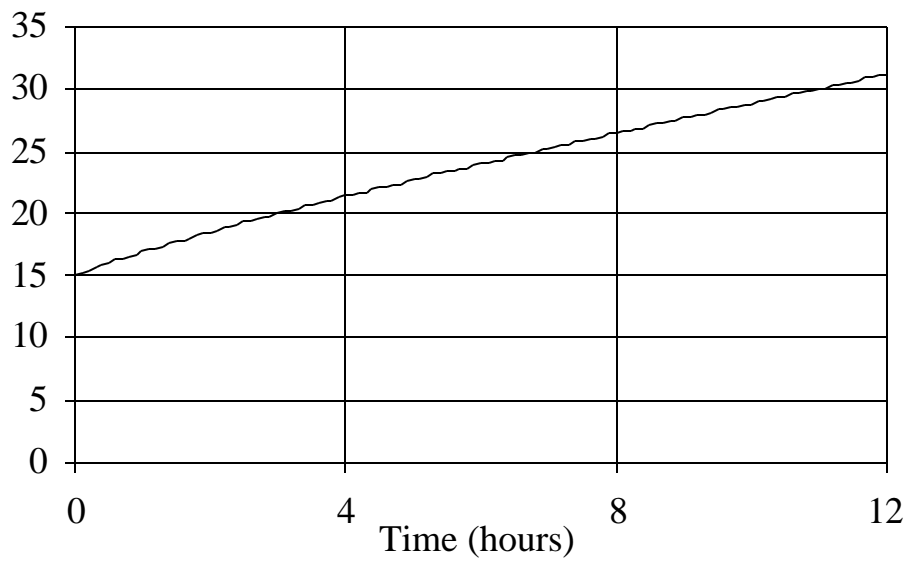
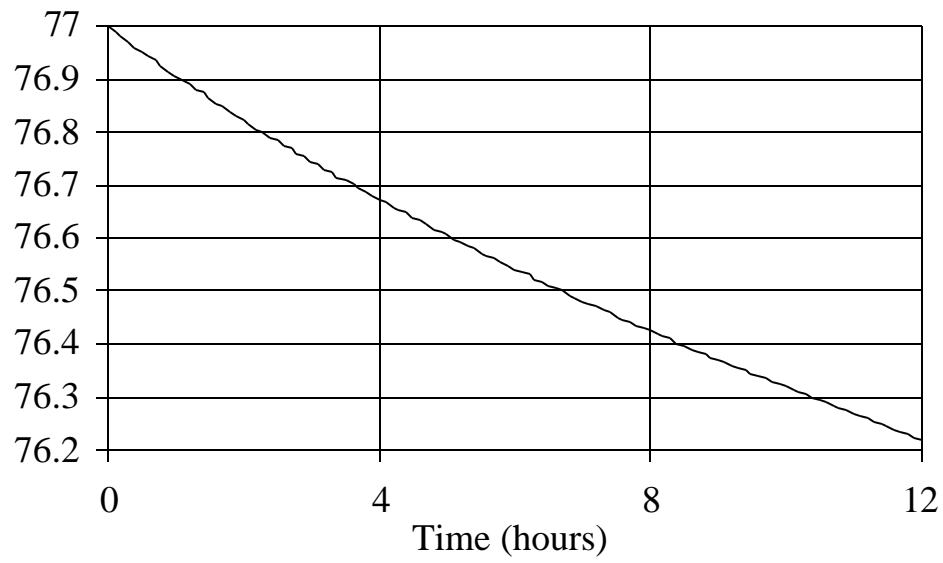
When protons (and antiprotons) are injected into a collider, a number of affects determine the evolution of the luminosity with time:

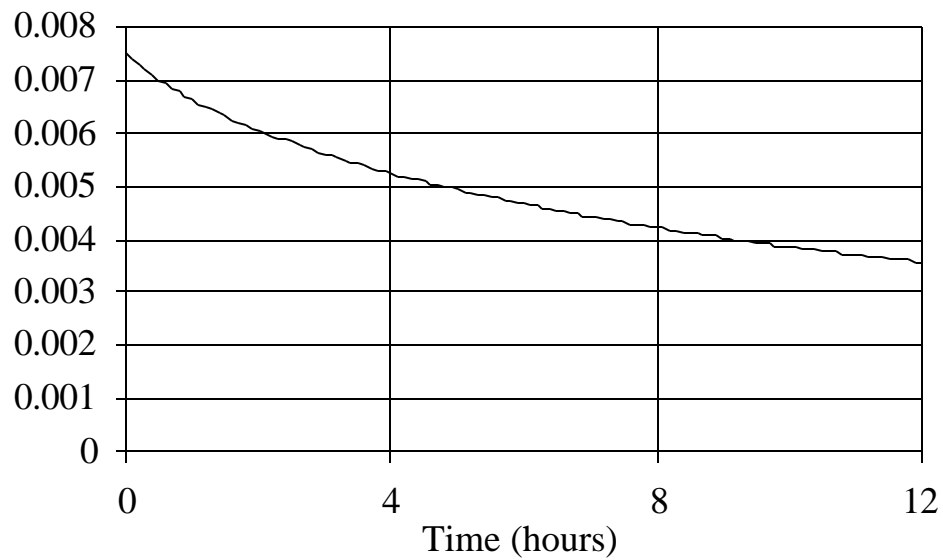
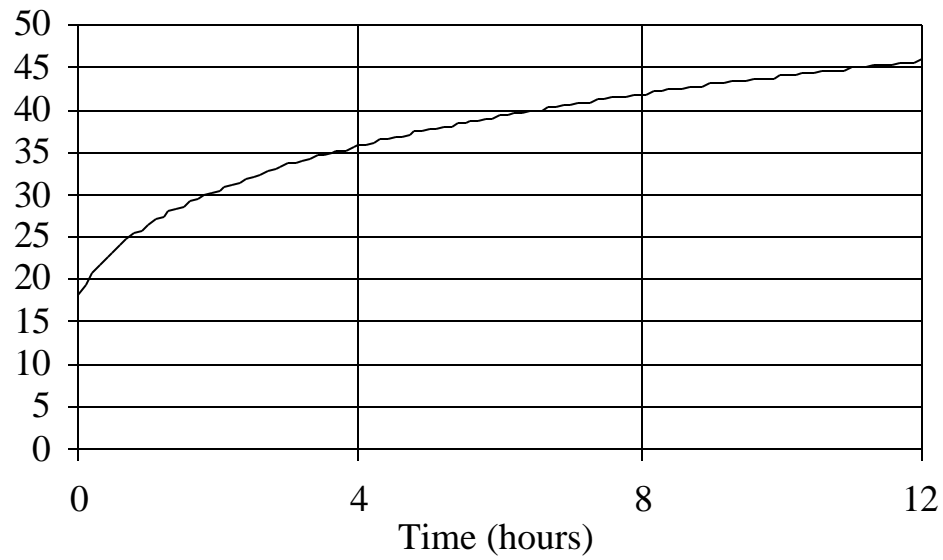
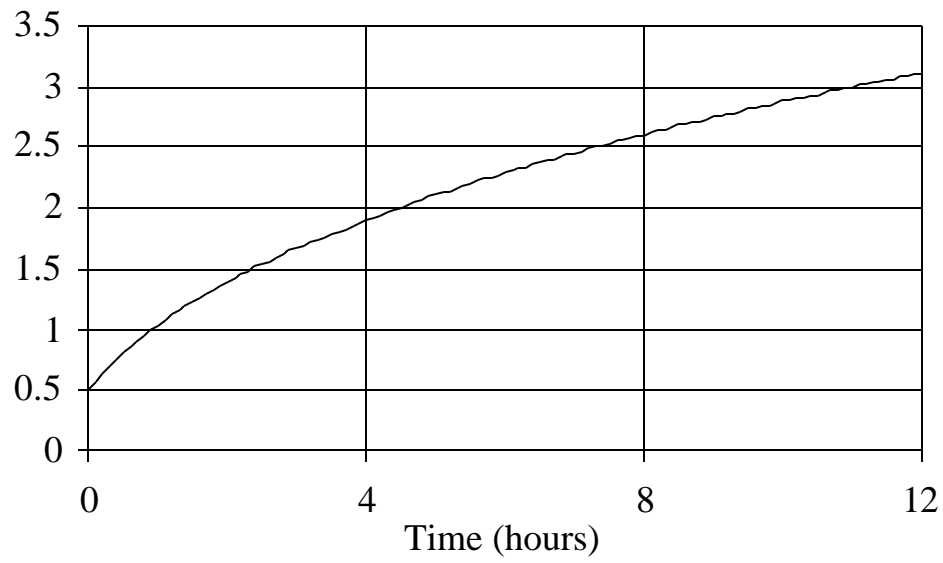
- 1) Particle Loss due to Collisions (Luminosity Dependent)
- 2) Particle Loss due to Residual Gas Molecules
- 3) Emittance and Bunch Area Growth due to Noise
- 4) Emittance and Bunch Area Growth due to Intrabeam Scattering

Over the years, some pretty good models have been developed for understanding this evolution. Below are some simulation results for a 3 TeV proton-proton hadronic B-Physics collider.

Parameter	Tev
Beam Energy (TeV)	3
Initial Emittance (pmmmr 95% inv)	15
Beta-Star (m)	3
Initial Bunch Area (eV-sec)	0.5
Initial Bunch Intensity (E9)	77
Number of Interaction Regions	2
Revolution Period (kHz)	8.8
Number of Bunches	3023
Emittance Growth Rate (pmmmr/hr)	1
Bunch Area Growth Rate (eV-sec/hr)	0.03







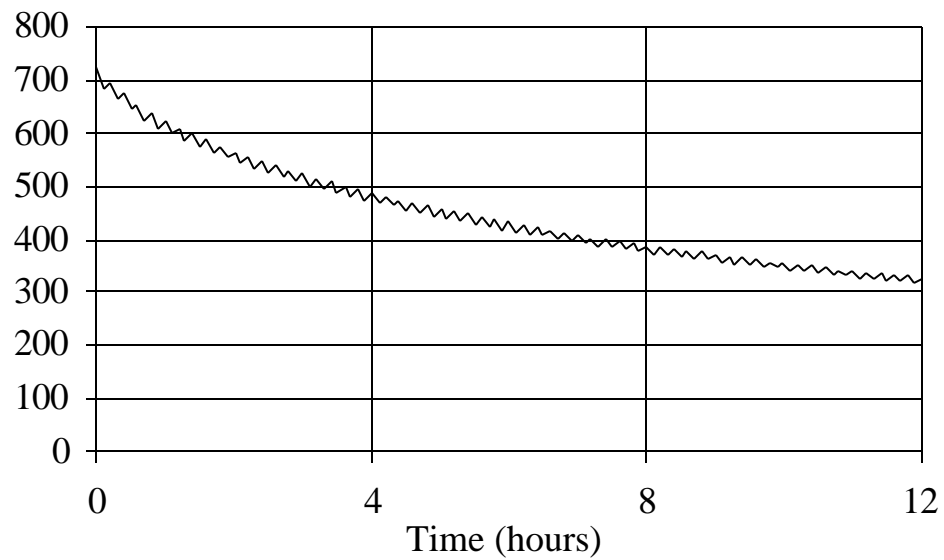
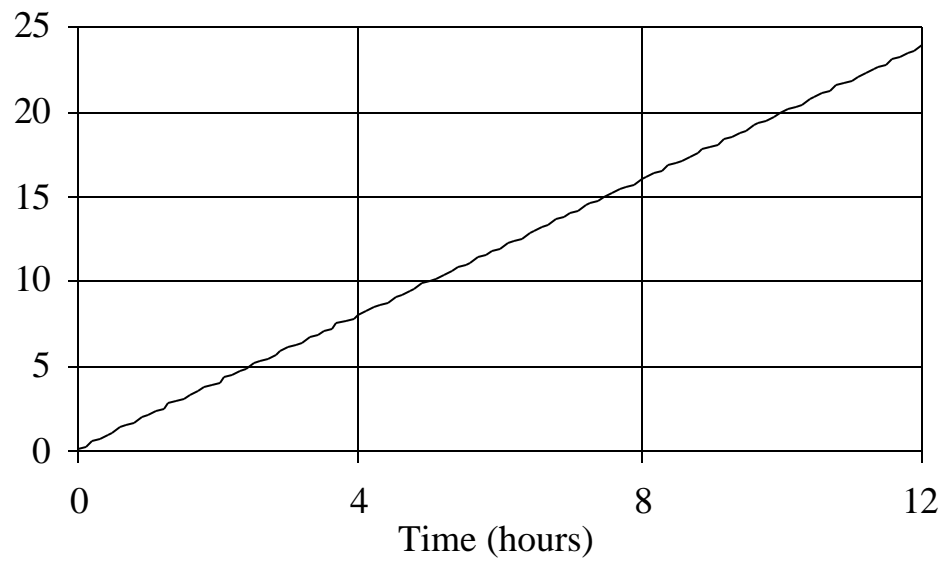
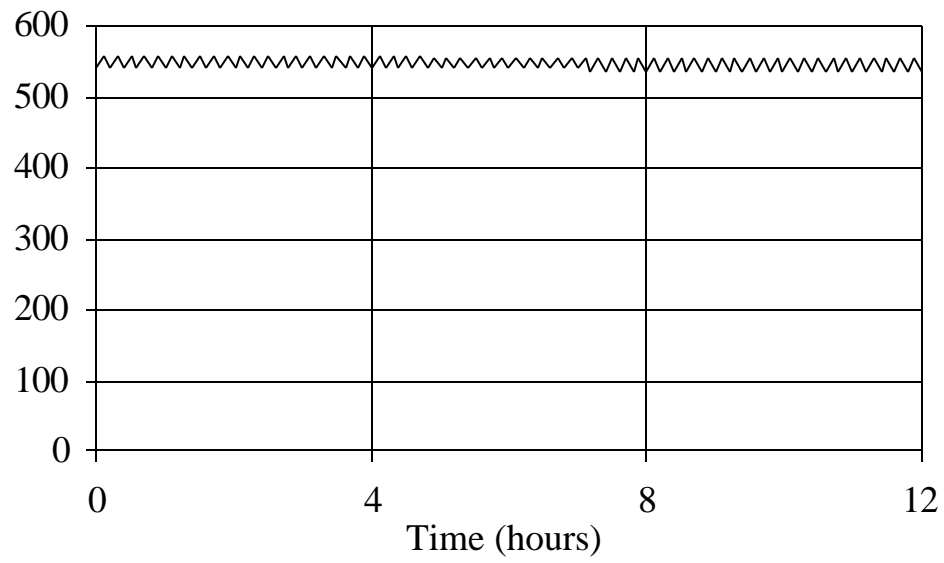
Luminosity Leveling

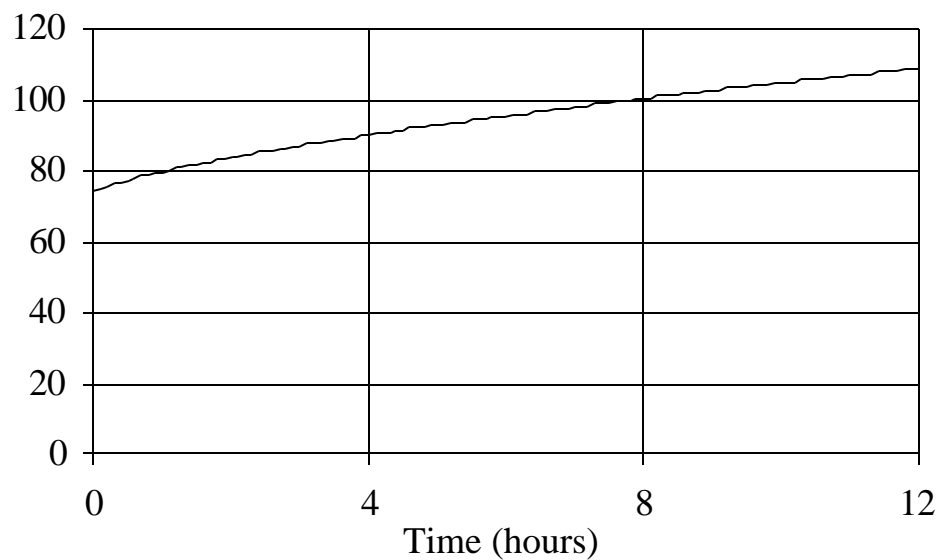
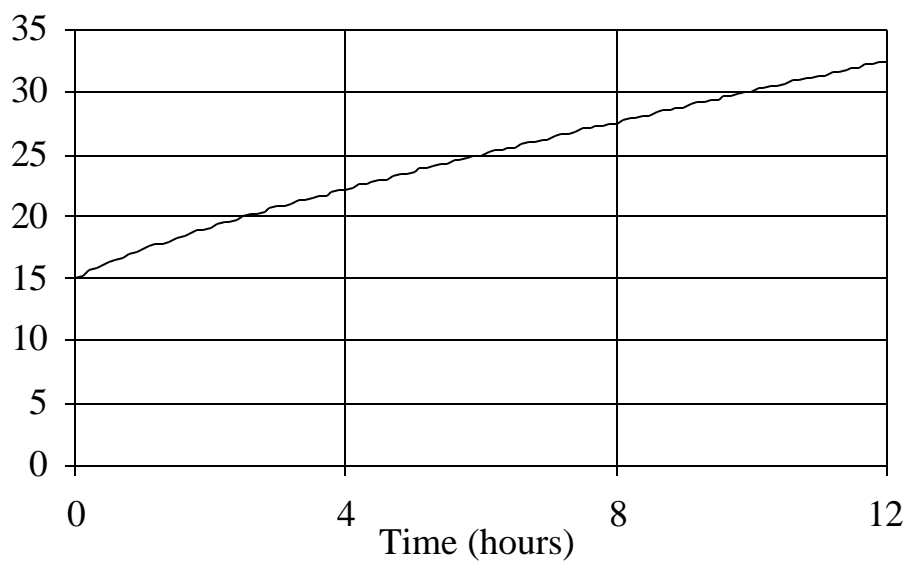
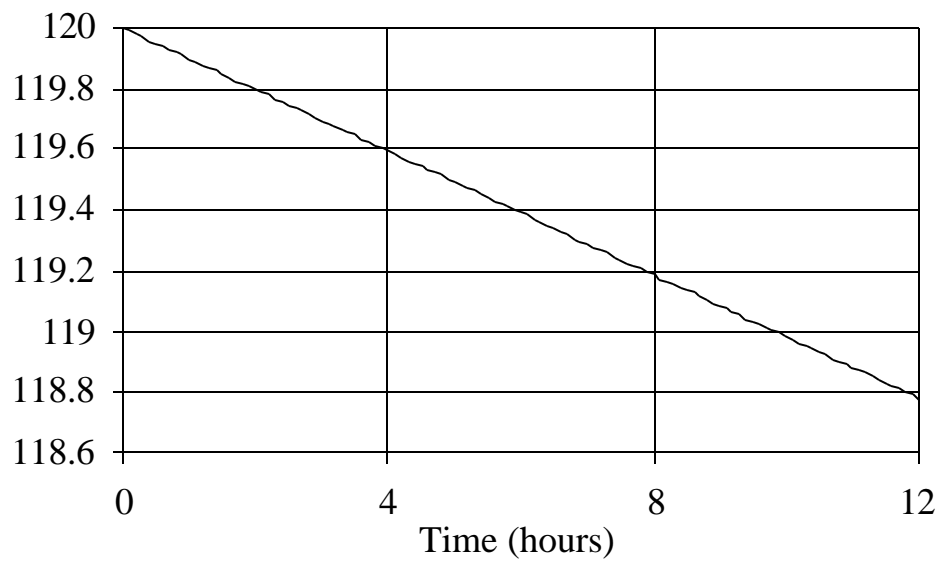
The problem with the above scenario is that most of the time the detector is not running at the optimum number of interactions per crossing and therefore at the peak luminosity.

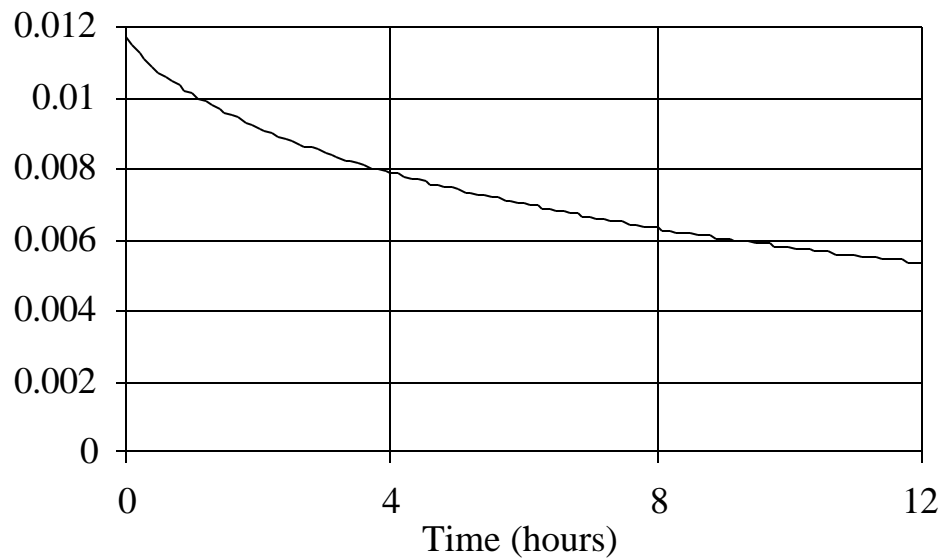
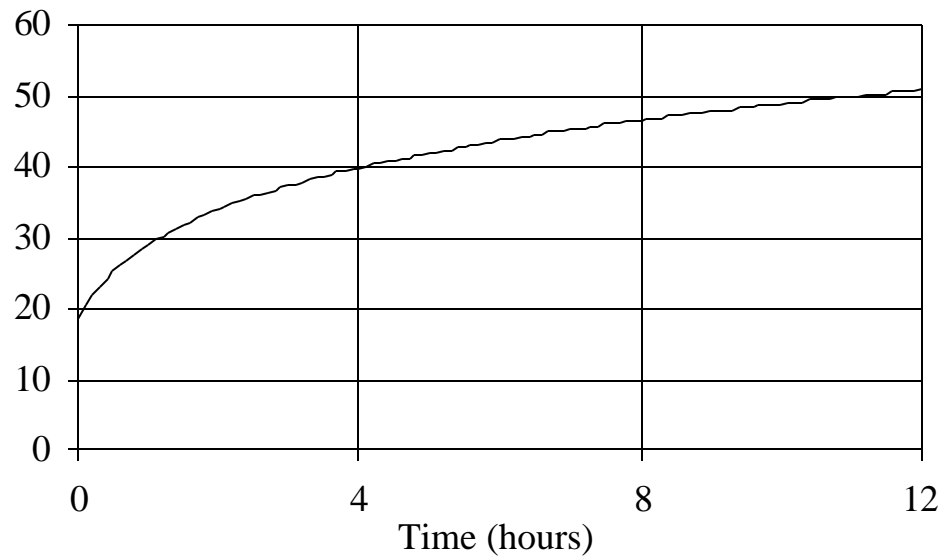
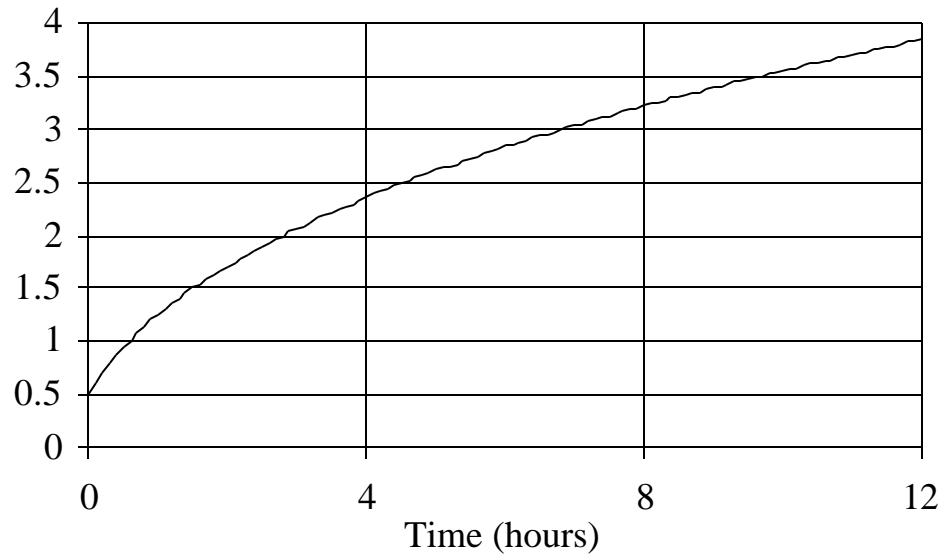
In Run II in the Tevatron Collider we will employ a new technique called "Luminosity Leveling". By adiabatically changing the strengths of the low-beta quadrupoles, the rms beam size is changed in order to keep luminosity constant.

In the simulation below one example of luminosity leveling is presented.

Parameter	Tev
Beam Energy (TeV)	3
Initial Emittance (pmmmr 95% inv)	15
Initial Beta-Star (m)	723
Initial Bunch Area (eV-sec)	0.5
Initial Bunch Intensity (E9)	120
Number of Interaction Regions	2
Revolution Period (kHz)	8.8
Number of Bunches	3023
Emittance Growth Rate (pmmmr/hr)	1
Bunch Area Growth Rate (eV-sec/hr)	0.03







Introduction to "Tevatron-B"

Because of the >10 year time to design and approve an accelerator and the >10 year construction time required by limited funding profiles, it is important for the hadron labs FNAL & CERN to develop a leap-frog strategy in which one lab designs the next step while the other lab is building the present step.

Therefore, FNAL has begun the design and R&D for the next machine after the LHC, sometimes called the VLHC (very large hadron collider). The preliminary goal is to build a proton-proton collider at FNAL with 100 TeV in the center-of-mass (50 TeV/beam).

Circular accelerators can only operate over a 20:1 range of beam momentum due to iron saturation and remnant fields. Because the FNAL Main Injector has an extraction energy of 150 GeV, a new accelerator which increases the beam energy from 150 GeV to 3 TeV is needed for injection into the VLHC. This allows the VLHC to reach 60 TeV/beam.

It is our proposal to build the 3 TeV accelerator with the same inexpensive super-ferric magnet technology planned for the VLHC. The cost **GOAL** (not estimate) for this machine is = 500 M\$, about the price of an e^+e^- B-Factory.

The main reason for building this 3 TeV machine first is to demonstrate that:

- 1) The super-ferric magnet technology works
- 2) The super-ferric magnet technology is inexpensive
- 3) Demonstrate the reduced cost of modern tunneling
- 4) **That it is possible in the U.S. to build an accelerator under existing communities**

The key for making the incredibly low project cost goal a reality is the new magnet technology proposed by Bill Foster. This magnet abandons the costly cosine-theta design, returns to 2 Tesla iron dominated magnets, but still uses superconducting cable to carry the current.

- A 2m prototype has already been successfully built. A 1 m prototype has already been powered and measured.
- This year we expect to build and test a 30 m long prototype.

Because the magnets are weaker, the circumference of the accelerator is larger. For the 3 TeV machine the circumference is 34 km, 10x larger than the present Main Injector/Recycler construction project. Therefore, it is vital to reduce tunneling costs.

- We have been actively discussing micro-tunneling options with new high-tech companies.
- This year we expect to start a tunneling R&D program at nearby rock quarries who are already in the layer of rock we would tunnel in.

The Pitch

This is a green field accelerator. It has no other mission than accelerator considerations. It would be MUCH more likely to be promptly approved if it had a physics case which was relatively inexpensive and non-challenging.

Why not B-physics?

Project Goals (Cost & Schedule)

As stated, the project goal is to come in below 500 M\$. To date this cost is dominated by costing traditional tunneling technology. If micro-tunneling is found to be feasible, this cost could come down by $\approx 2\times$ and the project cost could be as low as 300 M\$.

The schedule depends on how badly the HEP community wants to do this project. Below is a personal scenario which could be achieved:

Fiscal Year	Tevatron-B Tasks	Limitations and Competition
1998	Magnet/Tunnel R&D	Work on MI Project
1999	Magnet/Tunnel R&D	Finish MI Project
2000	Write Design Report	NUMI is Funded
2001	Get DOE Approval	NUMI is Funded
2002	Start Tunneling	NUMI is Funded
2003	Start Magnets	NUMI is Finishing
2004	Tunneling Complete	Tevatron33 Underway
2005	Magnets Complete	Start VLHC Designing
2006	Commissioning	Tevatron33 Finishing
2007	Do B-Physics	Write VLHC TDR
2008	Do B-Physics	Get VLHC Approval
2009	Do B-Physics	Get VLHC Approval
2010	Do B-Physics	Start VLHC Funding